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Abstract

Recently, an increasing off-set between tree-ring based temperature reconstructions and measured temperatures at high latitudes has been reported, the so called "divergence problem" (here "divergence effect"). This "divergence effect" seriously questions the validity of tree-ring based climate reconstructions, since it seems to violate the assumption of a stable response of trees to changing climate over time. In this study we eliminated the "divergence effect" in northern Alaska by careful selection of individual trees with consistently significant positive relationships with climate (17% of sample) and successfully attempted a divergence-free climate reconstruction using this subset. However, the majority of trees (83%) did not adhere to the uniformitarian principle as usually applied in dendroclimatology. Our results thus support the notion, that factors acting on an individual tree basis are the primary causes for the "divergence effect" (at least in northern Alaska). Neither different detrending methods nor factors acting on larger scales such as global dimming or an increase in UV-B radiation could explain our results. Our results also highlight the necessity to adapt the methods of paleoreconstruction using tree rings to account for non-stable climate growth relationships as these are found in the vast majority of sampled trees and seem to be the norm rather than the exception.

1 Introduction

Tree ring based climate reconstructions are the main basis to evaluate whether the recent warming is unprecedented over the last centuries to millennia (Esper et al., 2002; D'Arrigo et al., 2006). These reconstructions are based on the assumption that the relationship between climate and tree growth is linear and stable over time (often called the "uniformitarian principle"). It is thus unfortunate that tree ring indices developed from sites formerly considered temperature sensitive, show a weakening (instability) of the relationship between growth and temperature in the late 20th century (Jacoby and

D'Arrigo, 1995; Briffa et al., 1998a and b; Jacoby et al., 2000; Lloyd and Fastie, 2002; Davi et al., 2003; Briffa et al., 2004; Wilson and Elling, 2004; D'Arrigo et al., 2006, 2007; Wilson et al., 2007). Temperatures are rising faster than the tree ring proxies can follow, so that a model developed from these tree ring proxies under-predicts the late 20th century warming. This has been termed the "divergence problem" by D'Arrigo et al. (2007), and it raises valid questions about the usability of tree rings in climate reconstruction (NRC 2006). Here we refer to the "divergence problem" as the "divergence effect" to not convey any judgement by the wording. The "divergence effect" is for now considered unique to the 20th century and sites north of 55° N (Cook et al., 2004). In a recent analysis, Büntgen et al. (2008) did not find any evidence of the "divergence effect" in the European Alps (44–486° N) providing further evidence that this might be a high latitude phenomenon.

Several hypotheses for the "divergence effect" have been formulated (see summary D'Arrigo et al., 2007), among them global dimming, enhanced UV-B radiation, local pollution or tree specific moisture stress, methodological effects (e.g. detrending method of tree ring data) and selection of the target climate data (e.g. maximum versus minimum temperatures, urban versus rural stations, local versus gridded climate data).

Here, we test several of these hypotheses in northern Alaska, because Alaska is one of the regions with the strongest warming trends globally (0.53°/decade in June–July) during recent decades (McBean et al., 2005) and the region from where a divergence between tree growth indices and climate parameters was first reported (Jacoby and D'Arrigo, 1995). Recent warming in Alaska seems to have pushed some but not all trees over a physiological growth threshold (Wilmking et al., 2004) with the result that additional warming does not lead to increased growth, but rather reduced growth probably due to moisture stress (Lloyd and Fastie, 2002; Wilmking and Juday, 2005). This shift in climatic growth control from temperature to moisture of some trees at a site has resulted in emergent sub-population behavior of northern treeline trees since the mid 1970s, not only in Alaska (Wilmking et al., 2004; Driscoll et al., 2005; Wilmking and Juday, 2005), but the circumpolar north (Wilmking et al., 2005; Pisaric et al., 2007).

Using remote sensing a widespread "browning" of the boreal forest has been detected (Goetz et al., 2005; Bunn et al., 2007), which could be interpreted as the regional manifestation of tree specific moisture stress (Barber et al., 2000).

This paper extends the previous findings in the following way: 1) We use regional curve standardization instead of traditional detrending (as in the previously mentioned studies); 2) We test if the recent emergent sub-population behavior can lead to a "divergence effect" if undetected; 3) We specifically test the stability of the climate growth response of sub-populations of trees in northern Alaska over time and 4) attempt the possibility of a new climate reconstruction for northern Alaska taking into accounts the results from the first three steps.

2 Materials and methods

For this study we used raw data sets from northern treeline in Alaska which extended into the year 2000 from the International Tree Ring Data Bank (ITRDB) (AK 047-53) and a new data set from the author's collection (KGF1 in Western Alaska) (Fig. 1), all from Picea glauca Moench (Voss), the treeline building species in northwestern North America. For site information see Wilmking et al. (2004) and Wilmking and Juday (2005) for AK 047-053 and Wilmking et al. (2006) for KGF1. Raw measurements (0.001 mm precision) were crossdated visually and with the Program COFECHA and dating errors adjusted accordingly.

We then proceeded with two parallel lines of investigation: 1) All series from a site were included in a site chronology using Regional Curve Standardization (RCS) and the program ARSTAN (standard chronology), 2) Only those trees from a site which showed a significant positive relationship with June/July mean monthly temperatures throughout the 20th century (CRU data closest to each site, Mitchell and Jones, 2005) were used to build a positive responding site chronology using the RCS detrending method and the program ARSTAN (standard chronology). We used RCS due to its good ability to capture long term-trends (Briffa et al., 1992; Esper et al., 2002). Averaging the seven site chronologies obtained by method (1) resulted in the northern Alaska tree ring composite and averaging the seven positive responding site chronologies obtained by method (2) resulted in the positive responding north Alaska tree ring composite.

We then checked the consistency of the growth responses of each of the two tree ring composites over time with the program DENDROCLIM2002 (Biondi and Waikul, 2004) using a 31 year moving intervals to be able to compare our results to D'Arrigo et al. (2007) and regional CRU climate data (Mitchell and Jones, 2005).

For the climate reconstruction, we only used the positive responding north Alaska tree ring composite. Cross-correlation among the contributing site chronologies were high, indicating a common factor influencing growth (Table 1) and the relationship between growth and climate parameters was consistently significantly positive (Fig. 2a). For the actual reconstruction, we used principle component (PC) regression analysis, using the first PC (eigenvalue 4.05). We tested several calibration-verification periods (Table 2) to check the reliability of our calibration model. All the calibration models captured the significant statistics in the verification periods (except RE in the 1951–2000 verification period). Finally, to capture the low frequency variability, we used the 1901–2000 calibration model for reconstructing June–July temperature.

3 Results

From the 516 trees/772 series sampled along the 1000 km long transect spanning the seven sites in the Brooks Range, only 133 series or ~17% of the sample were found to show a consistent significantly positive relationship with climate parameters during the full period of record available (1901–2000). This positive correlation was strongest with June–July temperatures during the year of growth, and, even though constantly above the significance level, varied in strength over time (Fig. 2a). All other 639 series (or 83% of samples) showed non-stable or non-significant climate growth relationships over time, such as mostly recently negative or non-significant relationships with climate parameters as noted in other studies (Wilmking et al., 2004, 2005; Driscoll et al., 2005; Wilmking and Juday, 2005; Lloyd and Bunn, 2007).

The simple positive responding northern Alaska tree ring composite developed from the trees with a stable relationship with climate showed no significant divergence against the climate target parameters contrasting other studies from the same or similar regions (D'Arrigo et al., 2007). The tree ring index followed the temperature data closely over the period of record, including the last distinct increase in temperature since the mid 1970s (Fig. 2b).

However, by including trees with non-stable relationship between growth and climate we could simulate a "divergence effect". The simple northern Alaska tree ring composite developed from all sampled trees showed a decreasing relationships with June–July temperature since about 1960 (Fig. 2c), and as a result, the tree ring index diverges from the temperature data in the last decades mirroring published tree ring chronologies and composites for this region remarkably well (D'Arrigo et al., 2007) (Fig. 2d). The offset between temperature data and tree ring record was most notable at the end of the 20th century, but also some divergence existed in the first decade of the 20th century.

We then developed a reconstruction of June–July temperatures from the consistent positively responding trees, which does not show a divergence against actual measured climate data (Fig. 3). A slight underestimation of the recent warming trend (1970–2000: 0.42°/decade tree ring proxy; 0.53°/decade June–July temperature) occurs, however, the slopes of both regression lines are not significantly different from each other ($p>0.4$).

4 Discussion

Our results suggest that the previously reported decrease or reversal in overall temperature sensitivity of ring-width chronologies in Alaska (Jacoby and D'Arrigo 1995; Briffa et al., 1998a; Lloyd and Fastie, 2002; Davi et al., 2003; D'Arrigo et al., 2007) might have been to a large degree due to the inclusion of individual trees with a changing relationship of growth to climate. These trees might experience increasing stress due to a moisture deficit (Barber et al., 2000; Lloyd and Fastie, 2002; Wilmking et al., 2004), do not show a consistent relationship with one climate parameter and thus should 1) not be included in chronologies with trees showing consistent climate-growth relationships and 2) not be used for climate reconstruction.

However, even though the majority of trees in northern Alaska changed in climate sensitivity over time, it was possible to identify a sub-population of trees showing a consistent and significant relationship between growth and climate that reliably followed the recent warming trend. Using only those trees it was possible to attempt a climate reconstruction, which showed no significant divergence at the regional scale. However, this approach (also called "cherry-picking"), has inherent pitfalls and drawbacks and can generally not be recommended for a climate reconstruction. On the one hand, the sample size necessary in this study to achieve enough replication through time, was extremely large and on the other hand the question remains how reliable a climate reconstruction is, which uses only 17% of a sample.

The method used to remove the age-related growth trend in the sampled trees (RCS in this study, traditional in other studies, e.g. Wilmking et al., 2004, 2005; Driscoll et al., 2005; Pisaric et al., 2007) seemed not to influence the occurrence of sub-population behavior. While the detrending method cannot completely be ruled out as a contributor to the "divergence effect", it seems rather unlikely to be the main cause at these sites.

Our results also do not support any large-scale explanations, such as "global dimming" or an increase in UV-B radiation (D'Arrigo et al., 2007), since all trees at a particular site with no tree-to-tree competition should be affected by these phenomena simultaneously and not only some individual trees (i.e. one sub-population). However, particular environmental forcing mechanisms might be more effective on trees once they are stressed.

Extending this logic, our results also do not support the hypothesis that the use of differing temperature records (such as maximum/minimum versus averaged temperatures as it might be the case in the southern Yukon Territories, Canada (Wilson and Luckman, 2003) or gridded versus local climate data) is the primary cause for the "divergence effect" in northern Alaska. In this case, a clear "divergence effect" should also exist between the climate reconstruction using only the sub-population of consistently positive responding trees and the temperature record (averaged mean monthly temperatures), which is not evident from our results (Fig. 3). However, the slight (but not significant) underestimation of the recent warming trend by our reconstruction warrants further investigation.

Our results point mainly to one single reason for the occurrence of a divergence between tree growth and temperature data: Most sampled trees changed in climate sensitivity over time, in other words, a linear interpretation of the uniformitarian principle does not hold for the majority of the trees in our study. Instead, our results suggest that during times of rapid change in environmental conditions (e.g. warming) a simple ecological parameter (such as moisture stress, Barber et al., 2000) acting on most but not all trees in a given site can lead to diverse growth trends and emergent sub-population behavior, where some trees still benefit from the changing conditions (probable future survivors) and remain sensitive to temperature. Other trees are not as adapted, will be increasingly impacted, e.g. become sensitive to moisture due to temperature-induced drought stress (Barber et al., 2000) and might finally perish. The underlying mechanism for the "divergence problem" (D'Arrigo et al., 2007) thus might be, at least in northern Alaska, the ecological adaptation of a species to rapidly changing climate conditions.

The observed divergence in the first decade of the 20th century (Fig. 2d) is most probably due to the climate record at these sites at that time. Here we used gridded climate data, which is based on topographic modeling of the interpolation between climate stations. However, in the early part of the 20th century, no climate records exist from central or northern Alaska (Fairbanks starts in 1906) and as such the gridded climate data set might be quite unreliable during these early time periods. However, during the end of the 20th century climate records are of high standard and the divergence observed during that time period is more likely not the result of the climate data but the tree ring data underlying the climate reconstructions.

The divergence at the end of the 20th century observed in some climate reconstructions might be the result of a chronology building process without taking into account the stability of each individual tree's growth response to climate over time, resulting in chronologies with mixed consistently temperature sensitive and recently non-temperature sensitive trees. The inclusion of trees with non-stable climate-growth relationships into a chronology with trees showing a consistent climate-growth relationship will dampen or even obscure the climate sensitivity of the chronology. The results of any correlation analysis between this chronology and climate (or other factors) are thus misleading, because different climate factors are differentially impacting individual members of the chronology.

Standard dendro-climatological techniques to assure a common signal in chronologies are usually calculated over a longer time period (e.g. Expressed population signal (EPS), r-bar) and thus might not capture recent changes in driving factors such as developing moisture stress in some trees, or, if most or all trees are impacted, fail to recognize an ecological change in climate predictor. The techniques used for chronology development and quality control should thus be adapted to rapidly changing climate parameters, and include, for example, a standard test of each tree's reaction to climate over time. These tests should also be extended to the widely used International Tree Ring Data Bank (ITRDB). Many investigators use this publicly available archive for tree ring data. However, at the moment, the quality control features of the ITRDB do not detect emergent sub-population behavior (e.g. Alaskan data sets from Wilmking et al., 2004; B. Bauer, personal communication, 2006), probably because the time period with sub-population behavior is short in relationship to the length of the record. In addition, specific site information of data archived in the ITRDB is often missing and as such, it is very difficult to impossible to examine the ecological mechanisms of the observed change in climate sensitivity over time, which might be due to microsite and microclimate differences, stand level dynamics such as “infilling”, or disturbance such as insect infestation, fire, or grazing. We thus recommend further expanding the database of the ITRDB to include detailed site and stand history descriptions and caution against the indiscriminate use of data downloaded from the ITRDB.

5 Conclusions

The so-called "divergence effect" questions the reliability of tree ring chronologies to accurately reconstruct past climate variability. Here we show that even though the majority of sampled trees in northern Alaska have unstable climate-growth relationships, careful selection of individual trees (not chronologies) revealed a subset with a consistently significant positive relationship with climate over time. Using this subset, the "divergence effect" at Alaska's northern treeline could be eliminated indicating that the mechanisms behind the "divergence effect" probably lie at the individual tree and not the chronology level.

It remains important to note that even though we sampled at classic locations for temperature reconstructions, the vast majority (83%) of our sample did not adhere to the linear interpretation of the "uniformitarian principle" in dendro-climatology and that the validity of a climate reconstruction using only a fraction of the sample remains questionable. This calls for concerted efforts to adapt the methods of climate reconstruction to include non-linear relationships between proxy (e.g. trees) and climate parameter (e.g. D'Arrigo et al., 2004).

The existence of a subset of trees with consistently positive climate-growth relationships within the majority of trees with changing climate growth relationships argues against any radiative explanations, such as "global dimming" or an increase in UV-B radiation as the main causes of the "divergence effect" in northern Alaska, since the impact should be evident in all trees and not just some trees at a site. Also, our results do not support the hypothesis that the use of differing temperature variables is the main cause for the "divergence effect" in northern Alaska. Instead, our results indicate that rapid climate warming might lead to a break-down of the consistent climate-growth relationship in large parts of the tree population and that only some parts of the population are able to take full advantage of the new conditions. The observed "divergence effect" in a climate reconstruction might then be due to the mixture of trees with stable and non-stable climate growth relationships in the analysis. Trees with stable-climate growth relationship from the same sites do not show a divergence at the regional scale (at least in northern Alaska). The question remains however, why hemispheric scale temperature reconstructions developed from chronologies which show no "divergence effect" at the local or regional scale, show a "divergence effect" at the hemispheric scale (Wilson et al., 2007). We hypothesize that by careful selection of individual trees (not chronologies) which show a consistent relationship between growth and climate parameter, this divergence might be further reduced on all spatial scales.

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Table 1. Cross correlation (1901–2000) of the seven RCS chronologies used to build the regional chronology. All correlations are highly significant, $p<0.0001$, indicating a common factor influencing growth.

	BRFR	BRNC	BRNF	BRSJ	BRHF	KGF1
BRCL	0.59	0.80	0.69	0.58	0.86	0.79
BRFR		0.59	0.62	0.54	0.59	0.58
BRNC			0.68	0.65	0.87	0.60
BRNF				0.63	0.69	0.47
BRSJ					0.57	0.42
BRHF						0.71

Table 2. Calibration-vertification statistics obtained in principal component regression analysis.

Calibration			Verification				
Period	$R^2_{adj.}$	F value	Period	R	T value	sign test	RE
1901–1950	30%	21.9***	1951–2000	0.57**	5.0*	50/34*	−0.40
1951–2000	31%	22.9***	1901–1950	0.56**	3.8*	50/32*	0.40
1901–1965	19%	16.0***	1966–2000	0.57**	5.2*	35/30*	0.32
1966–2000	33%	15.9***	1901–1965	0.45*	3.0*	65/54*	0.44
1901–2000	32%	47.5***					

$R^2_{adj.}$ is captured variance adjusted for degrees of freedom; r is spearman correlation coefficient; RE is the reduction of error (details given in Fritts, 1976). * $p<0.05$, ** $p<0.01$,*** $p<0.0001$.

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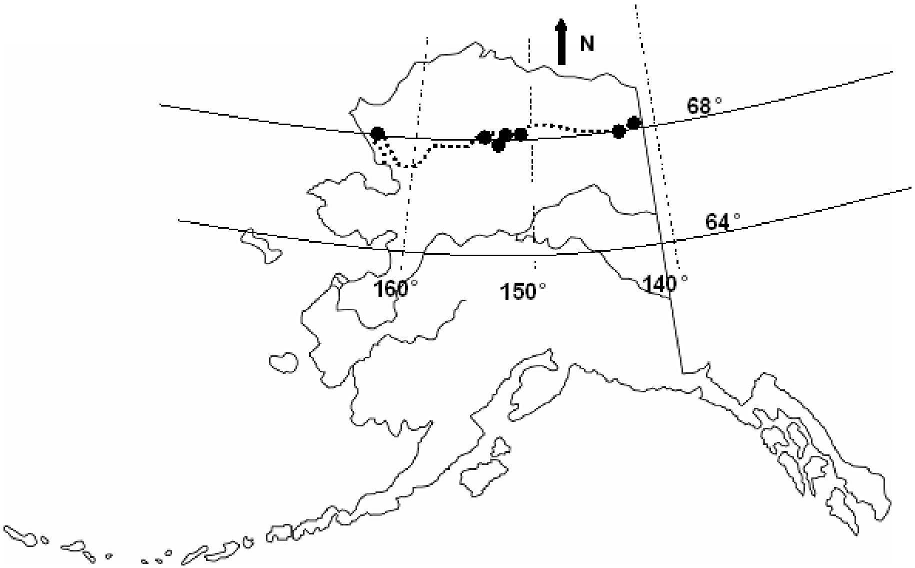

Fig. 1. Map of site locations in the Brooks Range, northern Alaska. From west to east, in brackets ITRDB contribution number: Kugururok River Forest I (KGF1, new site), Hunt Fork (ak052), Chimney Lake and North Fork (ak48 and ak49), Nutirwik Creek (ak50 and ak51), Sheenjek River (ak53), Firth River (ak047).

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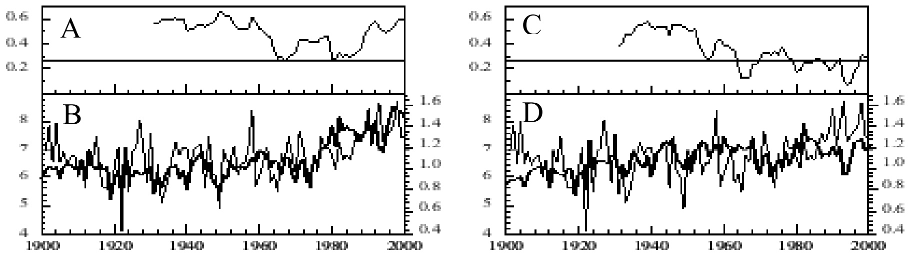

Fig. 2. 31 year running correlation (**A** and **C**, correlation coefficient on y-axis) and comparison between northern Alaska mean tree ring composite (RCS detrended, thick line) and actual June–July mean temperatures (thin line) for the Brooks Range CRU data set (**B** and **D**, temperature in °C on left and mean ring width index on right y-axis). Horizontal line in (A) and (C) is 95% significance cut-off. (A), (B): Only trees used with stable relationships with climate, (C), (D): All sampled trees used. No divergence exists when using only trees with stable climate-growth relationships (B).

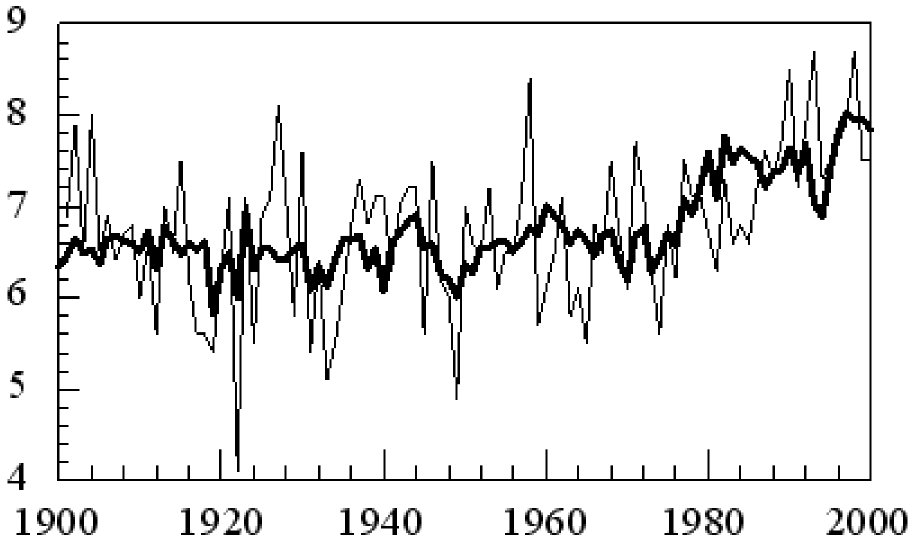

Fig. 3. Measured (thin line) and reconstructed (thick line) June–July temperatures (r^2adj = 0.32, 1901–2000). Temperature rise during 1970–2000 is significantly different from 1901–1969. Linear trends from 1970–2000 are significantly different from trends during the 1901–1969 period, but not significantly different from each other (actual climate data (0.53°C/decade), tree-ring based reconstruction (0.42°C/decade), p>0.4).